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POTENTIALS OF KENAF FIBRE IN BIO-COMPOSITE PRODUCTION: A REVIEW

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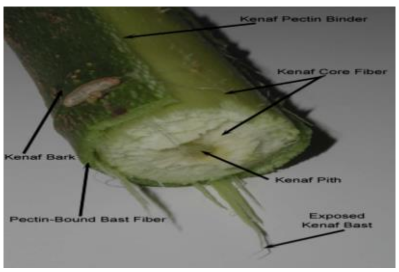
Graphical abstract



Abstract

Kenaf plants are blessing to mankind. Its high carbon dioxide (CO_2) assimilation rate and ability to clean the air by consuming large quantities of CO_2 and also absorbs nitrogen and phosphorous from the soil, which are the main cause of the greenhouse effect has made kenaf significant from the standpoint of environmental friendliness. Today kenaf fibres are envisioned as an alternative medium to replacing conventional materials or synthetic fibres as reinforcement in composites. The low cost, no health risk, low density, high strength and modulus, and availability of kenaf fibres in some countries has made it befitting for use in composites production. This review presents the potential and recent developments of kenaf fibre and its composites. Recommendations for future work are also made.

Keywords: Cellulose, fibre matrix interface, hydrophilic, hydrophobic, kenaf fibre, natural fibre composite, surface modification

1.0 INTRODUCTION

Kenaf plants have been extensively exploited over the past years among the many different types of natural resources. Today kenaf fibres are envisioned as an alternative medium to replacing conventional materials or synthetic fibres as reinforcement in composites [1].

Kenaf fibre is made from the bast (outer) and core (inner) fibres of the kenaf plant (*Hibiscus Cannabinus L.*). Kenaf fibre is native to Africa and Asia and one of the most widely cultivated natural fibres. It is an herbaceous annual plant that is cultivated commercially in the United States in a variety of weather conditions for a variety of uses, including oil spill absorbent, animal feed and as food in Ghana. Kenaf can grow up to a height of 2.4 to 6 m at an average of 150 days [2, 3]. Leaders in world kenaf production are India and China [4]. Agronomically, kenaf has advantages as regards to their resistance to climatic extremes, pests, and diseases [5].

2.0 GENERAL BACKGROUND

History had it that kenaf fibres are used in the manufacture of rope, sackcloth, and twine. Today the use of kenaf has transcended the traditional stereotypical application into a more specialized and commercial usage like paper production, animal feeds, manufacture of and oil spill absorbent agent, medicine, food additive, a platform for mushroom farming, environmental cleaning, oil and chemical absorbents [6-8].

Researchers have described kenaf plants to have a high carbon dioxide (CO_2) assimilation rate and ability to clean the air by consuming large quantities of CO_2, and also absorbs nitrogen and phosphorous in the soil. Kenaf fibre is significantly important due to its environmental friendliness and ability to control the greenhouse emission effect [2, 9, 10].

Webber III [11] elucidated that kenaf plant possesses three basic useful components. These components are the seed, the leave, and the stem. Fibre strands, proteins, oils, and allelopathic chemicals are the derivatives of these components. Figure 1a, b and c shows a photograph of kenaf plant, kenaf plant stem and its fibre.

(a) (b) (c)

Figure 1 (a) A photograph of kenaf plant. (b) Photograph of the cross section of kenaf plant stem (c) Photograph of a kenaf fibre

Normally the length of distinct kenaf fibre ranges between 2.0 to 6.0 m while the stem has a diameter between 25-51mm. The stem is straight and branchless and is composed of an outer layer (bark) and a core [12]. As a dicotyledonous plant, the stem has three layers; an outer cortical also referred to as ('bast") tissue layer called phloem, which constitutes 30–40% of the stem dry weight, and shows a rather dense structure, an inner woody ("core") tissue layer xylem, and a thin central pith layer which consist of sponge-like tissue with mostly non-fibrous cells which on the other hand, makes up the remaining 60–70% of the stem. The core reveals an isotropic and almost amorphous pattern. However, the bark shows an orientated high crystalline fibre pattern. Enzymatic and chemicals retting is seen as the easy means of detaching the bark and core from the stem of the plant [3, 13, 14].

Several groups of researchers have reported varying chemical compositions of kenaf fibres. Mazuki [15] and Davoodi [16] reported that the chemical composition of Kenaf fibres consists of cellulose (56–64 Wt. %), hemicellulose (21–35 Wt. %), lignin (8–14 Wt. %) and small amounts of extracts and ash. Also, Findings from Nishimura *et al*. [17] and [18] showed values ranging from 60–80% cellulose, 5–20% lignin (pectin), and up to 20% moisture.

Furthermore, [19] and [20] affirmed that kenaf bast fibre contains (cellulose 55%, ash 5.4% and lignin 14.7%) while Core fibre contains (cellulose 49%, ash 1% and lignin 19.2%).

Thi bach [21] indicated that kenaf Bast fibre contains (cellulose 52-59% and lignin 9.3-13.2%) while Core fibre (cellulose 44-46%, and lignin 18.3-23.2%). The large variation in the chemical composition is due to the variation in methodology of testing, varieties of the fibres type, position and or parts and age of plant.

Kenaf fibres are composite materials designed by nature. Their cell walls are basically comprised of a stiff, crystalline cellulose microfibril reinforced amorphous lignin, and/or hemicelluloses matrix. Kenaf fibres are made up of cellulose, hemicelluloses, lignin, waxes, and several water-soluble compounds. The most important constituents are lignin, hemicelluloses, and cellulose [1, 22].

The main constituent of natural fibre is cellulose in which kenaf fibre is one. Cellulose is the natural homopolymer (polysaccharides), where d-glucopyranose rings are connected to each other with β-(1→4) -glycosidic linkages. Cellulose is often found as a relatively high modulus, fibril component, of many naturally occurring composites [1]

Hemicellulose is made up of highly branched polysaccharides, including glucose, mannose, galactose, xylose, and others [23]. On the other hand, lignin (pectin) is thermally stable, but responsible for the UV degradation of the fibres. The primary (outer) cell wall is usually very thin (< 1 lm), but the Lignin is made up of aliphatic and aromatic hydrocarbon polymers positioned around the fibres. The strength and stiffness of the fibres are provided by cellulose components via hydrogen bonds and other linkages. Hemicellulose is responsible for biodegradation, moisture absorption, and thermal degradation of secondary cell wall composed of three layers. Of these, the secondary layer is the thickest and is the major contributor (at 80%) to the overall properties. The secondary layer is formed by microfibrils, which contain larger quantities of cellulose molecules [1].

The microfibrils run fairly parallel to each other and follow a steep helix around the cell. Furthermore, the micro fibril is composed of alternating crystalline and amorphous regions; the crystallite size is approximately 5–30 nm in a lateral direction and between 20 and 60 nm along the axis. Therefore, the cellulose molecules pass through several crystallites along the axis. This is called a fringed micelle structure [1].

In a previous study by [24], most of plant fibres contained 65–70% cellulose, which is composed of three elements, Carbon(C), Hydrogen(H) and Oxygen(O) with a general formula of $C_6H_{10}O_5$ that is crystalline. The lignin and other non-cellulosic substances are associated with the cell walls and their presence modifies the final properties of the fibre. The non-cellulose material is hardly ever completely removed from these fibres, mainly because it is prohibitively expensive to do so.

Absorption of moisture from the atmosphere in comparatively large quantities is attributed to Kenaf fibre a member of cellulose fibre family. This statement is supported by the works of [24] on plant fibres. Cellulose is hygroscopic and these cause most polymeric fibres to swell due to moisture absorption. This absorption leads to alterations in weights and dimensions, as well as in strengths and stiffness. This makes it prone to biological decay. To avoid this deficiency of natural fibre, and to make natural fibre suitable as reinforcement in bio composite production, a process known as fibre surface modification or treatment is carried out on the vegetable fibre as described in sub-section 2.2.

During the last 7-years (2007-2014), the identification of new application areas for this economical viable material has become an urgent task. The use of kenaf fibre as a reinforcement in composites has raised great interest and expectations amongst materials scientists, engineers and governments.

Foremost research works on kenaf fibres in the last 7-year period can be seen in this 4 ensuing area of categorization below:

2.1 Characteristics of Kenaf Fibre

Several studies [25-28] on the characteristics of kenaf fibre have been done using X-ray diffraction (XRD), Thermogravimetric (TG), Scanning electron microscope (SEM), Differential scanning calorimetry (DSC) and this has provided conjectural backing for the handling and use of this fibre. Physical, Mechanical, dielectric and thermal properties of kenaf fibre have been studied as seen in section 4.1.

2.2 Interface Properties Between Kenaf Fibre and Matrix Kenaf Fibre Properties

Modification of fibre surface to enhance its ability to bond with the matrix and to break the hydroxyl group in the cellulose, which makes the kenaf fibre hydrophilic and to reduce its affinity to water absorption. This process is achieved by chemical and thermal treatment methods [29-31].

2.3 Properties of Kenaf Fibre-reinforced Composites

Cement, Gypsum (hydrated calcium sulphate), thermoplastics (polyethylene, polypropylene, polystyrene, PVC), thermosets (epoxy, polyester), rubber (natural rubber, styrene-butadiene rubber) are all the different matrix employed in kenaf fibre-reinforced composites production. Very limited studies and theoretical models to predict the properties of processing methods, fibre length, fibre orientation, fibre-content fraction and fibre surface modification method on the physical and mechanical properties of kenaf fibre cement/concrete reinforced composites have been done in this past years [1, 32]. There is a great need for deep study on long term performance of kenaf fibre cement/concrete reinforced composites in tropical and temperate weather condition. This is to avail material engineers and structural designers' knowledge and data on the material properties and structural behaviour pertaining to serviceability performance. This is believed to be crucial to the promotion of the shift to this more efficient and sustainable concrete structure. To some extent the embracing of kenaf polymer composite is encouraging and a far-fetched research works as being carried out on it than on kenaf cement/concrete composite.

2.4 Kenaf/Glass-Fibre-Reinforced Hybrid Composites

Composites play significant role as a civil engineering material and their use has been increasing day by day due to their specific properties such as high strength to weight ratios, high modulus to weight ratio, corrosion resistance, and wear resistance.Several attempts have been made to hybridize Kenaf fibre material using synthetic (glass). This is as a struggle to reduce the overall use of synthetic reinforcement, to reduce the overall cost, and to enhance the mechanical properties.

Research articles which are related to kenaf fibre and published between 2007 and 2014 are enumerated in Table 1. It can be seen that research interest has changed from the fibre itself to kenaf fibre-reinforced composites and hybrid composites. However, the study of interphase between kenaf fibre and matrix remains a vital issue to dwell on.

Table 1 Published Research articles related to kenaf fibre between 2007 and 2014

	Number of Articles published			
Category	2007-2009	2010-2012	2013-2014	TOTAL
kenaf fibre Properties	[25] and [26]	[43] and [27]	[45]	6
Interface properties between kenaf fibre and matrix,	[46]	[47]	[44]	3
Properties of kenaf fibre-reinforced composites	[48] and [49]	[50], [51], [52], [15] and [53]	[54], [55], [56], [57], [58], and [59]	13
Kenaf/glass-fibre-reinforced hybrid composites	[60]	[16]	[61], [32] and [62]	5
Review	[40]	[1] and [63]	[64]	4

3.0 ECONOMY AND APPLICATION OF KENAF FIBRES

The cost of kenaf fibre (0.55U$/kg) when compared to synthetic fibres like E glass (3.25US$/kg) and carbon (200 US$/kg) and S. steel (30US$/kg) is very low [33, 34]. Kenaf crop has been found to be an important source fibre for composites and other industrial applications. Recently, kenaf is used as a raw material and as an alternative to wood in pulp and paper industries for avoiding destruction of forests [35], also it is used as non-woven mats in the automotive industries [36], textiles [37] and fibre board [38]. Natural and wood fibre plastic composites have gained significant interest in the last decade. The retail value of this industry has grown nearly 16% annually since 1998, and valued at over $750 million [39].

4.0 KENAF FIBRE PROPERTIES

4.1 Physical and Mechanical Properties

Kenaf, like most other natural fibers, demonstrates low density, high specific mechanical properties, and is easily recycled [34]. Kenaf bast fiber has been reported to have superior flexural strength combined with its excellent tensile strength that makes it the material of choice for a wide range of extruded, molded and non-woven products as widely discussed by other authors [40].

Largely, the mechanical properties of cellulose fibres depend on the cellulose content and the spiral angle which the bands of micro fibrils in the inner secondary cell wall make with the fibre axis. To be precise, the structure and properties of natural fibres depend on their source, age, position, quality of harvest, the body of the plant from which the fibre is extracted, the extraction techniques and the environmental conditions of the site [41]. Also, it depends on the experimental conditions such as gauge length, strain rate, fibre diameter, and test temperature. Table 2 shows the properties of kenaf fibres as reported by different researchers. A comparative study of literature data by [42] as shown in Table 3 demonstrated the potential of kenaf fibre as a worthy reinforcing fibre with mechanical properties that provide a high performance eco-friendly polymer composite such as normal, lightweight, high strength concrete and high performance concrete. A comparative study of literature data by [42] as shown in Table 3 demonstrated the potential of kenaf fibre as a worthy reinforcing fibre with mechanical properties that provide a high performance eco-friendly polymer composite such as normal, lightweight, high strength concrete and high performance concrete. A comparative study of literature data by [42] as shown in Table 3 demonstrated the potential of kenaf fibre as a worthy reinforcing fibre with mechanical properties that provide a high performance eco-friendly polymer composite such as normal, lightweight, high strength concrete and high performance concrete.

Some researchers studied the thermal stability of kenaf fibres so as to be able to assess the possibility of their being used as reinforcement. Similar to other natural fibres, kenaf fibres showed three stages of weight loss. The first stage was due to water evaporation which continued up to about 120^{o}C.

The second stage started at about 218oC, this stage resulted from the generation of non-combustible gases such as CO_2 and formic and acetic acids. The third stage began at about 330^{o}C.

This occurred because of pyrolysis and the generation of combustible gases. Thermo gravimetric (TG) analysis indicates that the kenaf fibres were thermally stable below 218^{o}C. Hence, the fibres could be effectively used as reinforcement when the molding temperature was set under this temperature [25]. The TG curve of the kenaf fibres is shown in Figure 2.

Cao [25] went further to ascertain the effect of heat treatment on tensile property of the fibre using the X-ray diffraction (XRD) analyses. Figure 2 shows the result of their outcome and the Cellulose crystallinity index (CrI) was calculated according to the Segal empirical method described in the experimental section as presented in Table 4.

As seen from Figure 3, kenaf fibre exhibited a typical cellulose I pattern, a well-defended peak at 2θ=22°. The reflections peak at 22° corresponds to the 002 crystallographic plane of the cellulose I lattice.

Table 2 Properties of kenaf fibres reported by different researchers

Density (g/cm3)	Tensile strength (MPa)	Tensile Modulus (MPa)	Maximum strain (%)	References
1.45	930	53	1.6	[65]
1.4	284-800	21-60	1.6	[66]
-	930	53	1.6	[67]
-	41.4-214.0	6.8-15.3	0.47-1.39	[26]
0.749	223-624	11-14.5	2.7-5.7	[31]
-	295-1191	2.86	3.5	[68]
-	692	10.94	4.3	[60]
1.5	350-600	40	2.5-3.5	[50]
0.75	400-550	-	-	[52]
0.627	35.43-155.80	2824.44-11463.40	-	[69]
1.2	295	-	3-10	[70]
0.6	-	-	-	[53]
1.2	780	40,738	1.9	[28]

Table 3 Kenaf fibres and E-glass fibres properties [42]

Fibers	**Properties**						
	Density (g/cm3)	Tensile Strength (MPa)	E-modulus (GPa)	Specific (E/Density)	Elongation at failure (%)	Cellulose/Lignin (%)	Microfibril angle (Deg)
E-glass	2.6	2000	76	29	2.6	-	-
Kenaf	1.5	350-600	40	27	0.33-0.88	75-90	9-15

Table 4 CrL of untreated and heat treated kenaf fibre [25]

		Heat treated temperature(°C)				
	Untreated	130	140	160	190	220
Crl of kenaf fibre (%)	48.7	51.2	55.8	49.0	43.0	32.3

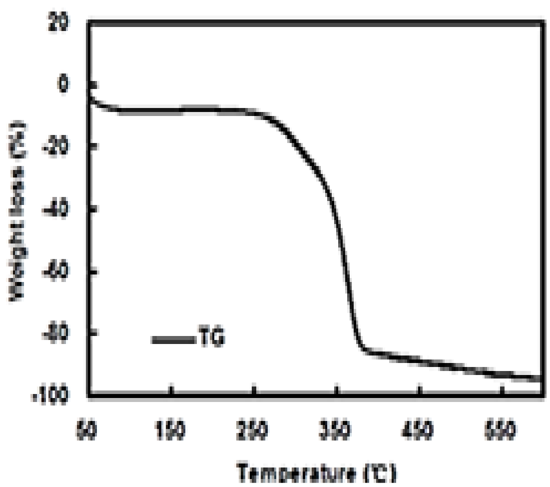


Figure 2 TG curve of the kenaf fibre [25]

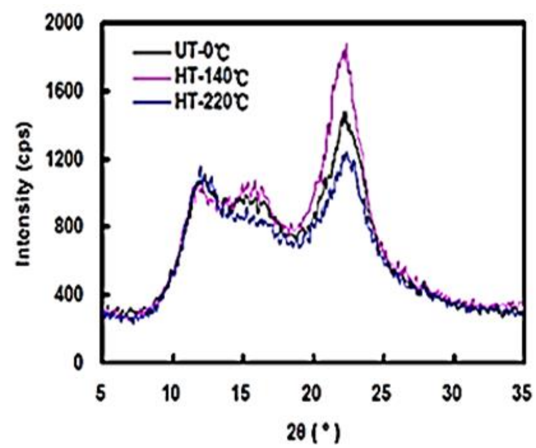


Figure 3 X-ray diffraction patterns of untreated and treated kenaf fibres. (HT: Heat Treatment) [25]

The maximum value of the intensity is clearly observed in the fibre treated at 140°C. Table 2 presents similar result and reveals that the CrI of the treated fibre at 140°C was higher than that of other heat temperatures and the untreated fibre. The increase of the CrI indicates the improvement in the cellulose structure and finally contributes to enhancing the tensile strength of the treated fibre. However, the CrI of the fibres treated at higher temperature, 190°C and 220°C, the fibre CrI decreased in comparison with that of the untreated. This lowered the tensile strength of the fibre, along with the thermal degradation of the fibre.

Du [26] reported the effects of high temperature and exposure duration on mechanical properties of kenaf bast fibre bundles (KBFB). Their Experimental results showed that temperature and duration of exposure of fibre to temperature have a significant interaction effect on the tensile modulus, while for the tensile strength interaction effect is significantly marginal at 10% significance level. Discovery from their investigation showed that tensile failure strain was significantly affected by temperature, not duration The heat duration seemed to have no significant effect to the KBFB tensile strength at the temperature of 130°C and above. The behaviour of KBFB decline in tensile strength due to temperature effect can be interpreted by the degradation process of cellulose, hemicellulose, and lignin composing the KBFB. In general, the KBFB failure strain decreases as the temperature increases. A significant decline in KBFB failure strain started at 150°C.

A hermetical alkali digestion process to obtain single cellulosic fibres from kenaf bast was developed in a study by [43]. The Hermetical alkali digestion process effectively removed the lignin and hemicellulose from kenaf bast fibres at 160°C. The α-cellulose content of the fibres was 92%. The average surface hardness and elastic modulus of the fibre digested at 160°C yielded improvement of 348.1% and 111.3%, respectively, compared with those digested at 80°C. The increase of cellulose content of the digested fibres resulted in an improved fibre surface hardness and elastic modulus. The digestion temperature had a significant effect on tensile modulus and tensile strength properties of the fibre. When the digestion temperature increased from 110°C to 160°C, the tensile modulus and tensile strength of individual fibres were reduced by 42.8% and 22.9%, respectively, while the elongation increased by 1.1%. The SEM images showed that the micropores were generated in cell wall structures for the fibres digested at 130°C and 160°C, providing the possibility to anchor nanoparticles into the cell wall.

The digested fibres without surface modification had a poor interfacial compatibility with the polypropylene matrix [43]. This an indication that the digested fibre still requires surface modification for it to be compatible with matrix for composite production [43].

The morphology of kenaf fibre surface was observed by [44] using SEM equipment. They observed that the chemical surface treatment causes a clean and rough surface on the fibre which is so important for interfacial bonding of cement or polymer and kenaf fibre as presented in Figure 4. The surface of untreated fibre was covered by lignin, hemicellulose and wax that chemical treatment can remove them from the area. Consequently, the treated fibre has non-smooth surface which can provide a better interlocking between cement or polymer and fibre.

They [44] also explain the effects of alkaline treatment with different NaOH concentration and immersion times, and put it that, increasing the NaOH concentration solution increases the cleanness and roughness of fibre surface. They conclude that 5% alkali solution at 3hr immersion time is the best for kenaf fibre treatment as shown in Figure 5, because it causes no tension on the fibre texture and structure as compared to 10% and 15% alkali solution. The high concentration of NaOH i.e. 10% and above may damage the fibre structure.

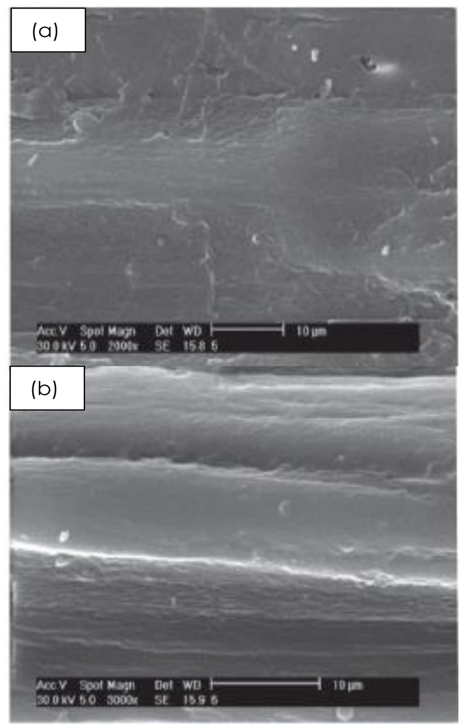


Figure 4 SEM images of untreated and treated surface of kenaf fibre [44] (a) Untreated Kenaf fibre (b) Treated kenaf fibre

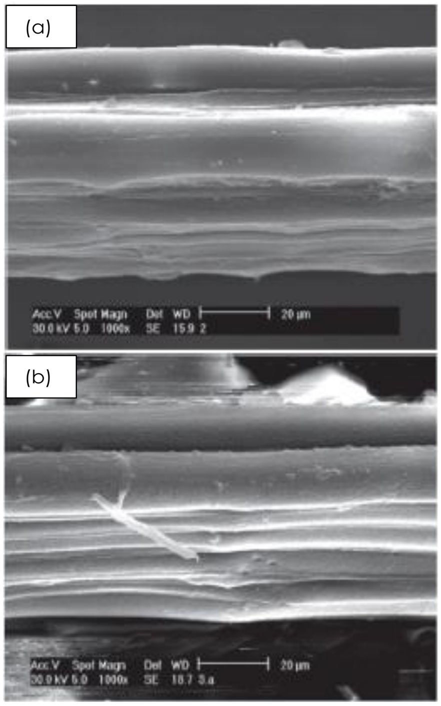


Figure 5 SEM images of the 5% alkali solution at 3hr immersion time alkaline treatment on kenaf fibre (a) Untreated Kenaf fibre (b) Treated kenaf fibre

5.0 CONCLUSION

The study revealed that kenaf fibre when compared to other fibres is more Eco friendly, lower in cost and lower in density. Kenaf fibres have very good mechanical properties. The specific stiffness is comparable to the glass fibre ones, and the price is 2 to 3 times lower than the glass fibres. The elongation at failure is also comparable to that of glass fibres. kenaf fibre Physical and mechanical properties are not only depending on its source, position and age, which will affect the structure and properties, but also on the experimental conditions, such as fibre diameter, gauge length, strain rate and test temperature. It is well known that the hygroscopic nature of kenaf fibres lead to it alterations in weights and dimensions, as well as in strengths and stiffness, but research has proved that this deficiency can be avoided and kenaf fibre can be made suitable as reinforcement in biocomposite production by a process known as fibre surface modification or treatment.

There is a need for extensive study on the effect of inclusion of kenaf fibre on the long term performance of kenaf biofibrous concrete composite (KFCC) in tropical and temperate weather condition. This will avail material engineers and structural designers' knowledge and data on the time dependent material properties and structural behaviour pertaining to serviceability performance.

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